Accelerator Division Impact Statement for the Mu2e Proposal

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Abstract

The impacts of the Muon to Electron Conversion Experiment ($Mu2e$) Proposal on the Accelerator Division and Fermilab accelerator facilities are outlined and tabulated. Particular attention is paid to the accelerator R&D and engineering design efforts required in the near future.

Contents

1 Overview and Starting Assumptions

The $Mu2e$ experiment proposal[1] relies on the use of spare 15 Hz cycles from the Fermilab Booster to provide protons to target at a time average rate of 1.8×10^{13} protons per second and assumes the Booster is operating at its full 15 Hz capacity. Summarizing the proposal, three Booster batches are momentum stacked into the existing Accumulator ring, using the Recycler Ring as a single-pass transfer line and other (mostly existing) beam lines for transport. The accumulated protons are then formed into a single bunch and transfered into the Debuncher ring, where a bunch rotation and capture occurs, forming a single ∼30 ns (rms) bunch. This beam is then resonantly extracted from the Debuncher over a period of 600 ms, during which time the next three bunches are prepared in the Accumulator. Two of these extractions can occur during a single 1.333 s Main Injector ramp during nominal NOνA operation without impact on the NOνA program. Details of the time line of events and accelerator requirements are found in the proposal, as well as in other documents available in the documents databases.[2],[3] Table A of the Appendix lists various beam and accelerator parameters for the experiment.

1.1 Comments on Booster Performance

In the proposal the Booster is expected to be operating at 15 Hz. The present Proton Plan[4] will get to about 9-10 Hz, but additional RF upgrades are required to reach full 15 Hz operation. These upgrades are foreseen by the $Mu2e$ collaboration as part of the on-going accelerator improvement program by AD. The total cost for these upgrades have been estimated and documented.[5] Further improvement in reliability would require the "solid state upgrade," estimated in [6], which is also seen as outside the scope of the $Mu2e$ program.

Additionally, the Proton Plan provides a new magnetic corrector system for the Booster. This system will allow full control of orbits, tunes, and chromaticity throughout the Booster acceleration cycle. It is envisioned that with this system the Booster will be able to perform at 15 Hz within the present limits for beam losses.

In all, the $Mu2e$ experiment expects to use a 15 Hz Booster with acceptable loss rates at a typical batch intensity of 4×10^{12} when it comes on line, projected to be around the year 2016. Other 8 GeV experiments being discussed, such as the Muon g-2 Experiment and microBooNE as examples, will also require the same Booster performance and hence these necessary upgrades might be considered as part of the overall facility improvement program.

1.2 Comments on NOνA and Mu2e

Essentially by design the $Mu2e$ experiment does not interfere with the operating cycles required for the NOνA experiment. In the event that NOνA is not running for an extended period of time or not at all, the $Mu2e$ experiment could in principle receive more cycles. If a 15 Hz Booster is available, then the

experiment would be able to run using the same scenario described in the proposal but with a repeat period of five Booster cycles rather than ten, doubling the average throughput to the target. But even in a scenario where the Booster can only run 10 Hz, say, and NOνA is not running, then in principle the experiment can receive beam at a 50% higher average rate than proposed.

2   Impact on Recycler/Main Injector

To save the expense of building a totally new transport line enclosure, it is proposed that protons be transfered to the Accumulator through the existing MI-8 line, through the Recycler Ring, and through existing antiproton transport lines. At present, the MI-8 line and the antiproton transport lines are tied to the Main Injector, not the Recycler. Thus, these capabilities must be introduced for $Mu2e$.

Injection into the Recycler from MI-8, is planned for the NOνA project (Accelerator NuMI Upgrade, or "ANU"). This presumably will be completed well before $Mu2e$. The present MI-8 line injects into the Main Injector which then performs a "mini-dip" by 45 MeV to transfer beam into the Recycler. How this energy discrepancy gets dealt with when injecting directly into the Recycler from the MI-8 line needs to be reconciled. This is true for ANU as well, and thus is assumed to be mitigated from within that project. Additionally, the stochastic cooling and electron cooling systems need to be removed from the Recycler to enhance the aperture for slip stacking and, again, is to be accomplished from within ANU.

Extraction from the Recycler into the P1 line, however, now will be required and in principle is the only new physical modification to the Recycler/Main Injector system necessary in the $Mu2e$ proposal. The area leading to the P1 line is complicated by numerous existing components and will require special effort leading to a final design.

It should be pointed out that should the Muon g-2 Experiment be adopted prior to $Mu2e$, it, too, will require the same extraction line. Thus, one could foresee two scenarios:

1. The g-2 experiment is conducted first, and thus the extraction line and necessary (for g-2) extraction kicker magnet are available for use in $Mu2e$, or

2. The extraction line is built for $Mu2e$ and a pulsed dipole magnet is used for steering into the extraction channel.

Since the Recycler is used only as a transport line, a fast kicker magnet would not be necessary for extraction for $Mu2e$ as in g-2. For purposes of this report, we will not assume the existence of the g-2 experiment, and assume that the transport line and a pulsed dipole are required.

3   Impact on Antiproton Source

The greatest impacts from the $Mu2e$ proposal on the accelerator complex reside in the Antiproton Source. A number of items will need to be addressed[7]:

1. Radiation safety will be a major issue for this use of these rings. The particle flux through the system is many orders of magnitude greater than presently encountered, and existing passive shielding is not appropriate. A "Booster-style" radiation safety system will need to be incorporated, and fencing of the area and perhaps restricted access to service buildings may all be necessary. This is a major effort and work to address this issue needs to begin very soon. As the AP3 beam line has passive shielding essentially identical to the rings, its assessment will need to be included in this effort.

2. In addition to personnel safety addressed above, measures should be taken to address the effects of increased radiation on the tunnel equipment as well as service building equipment and controls.

3. New or modified RF systems will be required for the Accumulator and Debuncher rings to provide capture and bunch rotation voltages appropriate for this application. As the slip factor is small in the Debuncher, its variation across the RF bucket during bunch rotation can be large and care must be taken to model this effect appropriately. The locations of the necessary RF equipment must be reconciled with the locations required for injection and extraction as discussed below.

4. Resonant extraction with a full width $\Delta p/p$ of 4% needs full attention, especially in the presence of strong space charge effects associated with the high beam intensity. Third- and half-integer slow spill scenarios need proper characterization and comparison and the extraction system properly designed including magnetic and electrostatic elements, and tune control system with air-core magnetic elements and appropriate feedback mechanisms. Estimates of expected inefficiencies and beam loss rates need to be generated. Specification of uniformity of particle "bursts" emanating from the Debuncher toward the experiment needs to be performed.

5. Stochastic cooling equipment from the Accumulator and Debuncher will need to be removed to provide the largest aperture available. Impacts on longitudinal and transverse impedances need to be examined.

6. Presently when 8 GeV protons are injected into the Accumulator the momentum spread of the injected beam more than fills the injection channel aperture. Assumptions about the longitudinal emittance from the Booster need to be verified.

7. As mentioned previously the Booster-MI-RR-Accumulator energy mismatch needs to be closely examined and mitigated. The Accumulator injection/extraction orbit energy is ~35 MeV greater than the MI nominal 8 GeV energy. This perhaps could be remedied by increasing γ_t in the Accumulator (toward its TeV I design value) and should be investigated.

8. The Accumulator injection/extraction orbit has negative horizontal chromaticity (and positive vertical chromaticity). This may not be correctable with the present sextupole and octupole circuits, and the injected beam could easily be horizontally unstable at the anticipated intensities.

9. Accumulator injection and extraction as well as Debuncher injection will require a redesign. In particular:

- The present kickers and septa (and their power supplies) almost certainly will not run at 15 Hz and will need to be upgraded.

- The transfer line between the Accumulator and Debuncher will need to be relocated to the AP50 region from the AP10 region, as AP10 will be used for extraction.

- The Accumulator extraction orbit will need to be determined. Three options to consider:

    - Extraction from core orbit (beam line must somehow cross the Accumulator).
    - Extraction from zero dispersion straight.
    - Extraction from the present injection orbit (requires additional RF ramp to move beam back to injection orbit).

    The Accumulator extraction scheme will determine the central Debuncher energy and the $Mu2e$ beam line energy.

- The revolution frequency difference between the Accumulator and Debuncher needs to be accommodated (frequency jump scheme?) for synchronous transfers to occur.

The final design of the beam transfer system will need to addressed the proposed momentum spread of beam coming out of the Accumulator and into the Debuncher, including the kicker(s) good field region.

10. The two rings have very different vacuum requirements at present ($\sim 10^{-11}$ torr in the Accumulator and $\sim 10^{-8}$ torr in the Debuncher) and the transfer line between them includes vacuum windows for separation. As beam will only reside at most several hundred milliseconds, as opposed to days, the vacuum requirements can be relaxed and the vacuum windows removed to prevent issues with transfers. This issue needs to be examined in detail and appropriate recommendations generated in light of the necessary redesign of the transfer line.

11. In general, Accumulator and Debuncher space charge effects need to be closely examined for the very high intensities being discussed. Peak bunch currents of about 20 A will be new to the accelerator complex.

12. At present, an external beam dump is foreseen in the beam line for tuning up the rings and slow spill, with "abort" situations being dealt with using beam inhibits of the 15 Hz operation. However, the possible requirement of an internal beam abort system in the Debuncher (and Accumulator?) has been raised. This needs to be formally addressed and, if required, possible civil construction may be necessary to properly enclose the abort dump(s).

13. Possibilities for gap cleaning in the Debuncher and/or Accumulator need to be examined. This could be part of the "extinction scheme" necessary for the experiment.

14. Compensation of non-linear chromaticity in the Debuncher may be required, through the use of decapole magnets. If deemed necessary, these would need to be added along with appropriate power supplies.

15. The Accumulator and Debuncher rings are instrumented to monitor mostly DC beam, whereas the $Mu2e$ operation will use sparsely bunched beam. Therefore instrumentation reconfiguration and upgrades will need to be examined in detail.

In summary, the $Mu2e$ experiment proposal requires many changes to the existing Accumulator/Debuncher synchrotrons, and mitigation of the radiation safety issues associated with the much higher particle throughput of these accelerators. It is also very demanding of the beam intensities, which, even if the rings can accommodate these intensities, may play havoc on the slow spill process because of the very large tune spread within the bunch.

4   Mu2e Beam Line

The Accelerator Division should provide the physics layout and engineering design of the $Mu2e$ beam line from the extraction point of the Debuncher to the experiment target. The exact location and layout is being investigated, but the total path length of this system will be approximately 200 m, which will require on the order of two dozen quadrupoles and relatively small amounts of bending along the way. The final design trajectory of the beam line will be negotiated between AD, the experiment, PPD, and FESS.

A major component of this beam line will be the "extinction insert" as required by the experiment, with appropriate shielding around the extinction collimation system. The extinction system as outlined in the proposal utilizes a pair of 300 kHz dipole magnets, which have been examined in the Technical Division with the power supply requirements looked at by AD/EE Support.[8] The requirements of this system need to be finalized and the system optimized and fully engineered. Included in this must be a discussion of the method and instrumentation required to measure and confirm a level of extinction of 10^{-9}.

Additionally, the beam line will require a beam dump to facilitate tuning up of Debuncher extraction. It may be that this beam dump should be incorporated after the extinction insert to aid in extinction measurements. In either case, proper instrumentation at (and to) the dump will be required to handle $\sim 10^{13}$ protons, as well as the much lesser demands on beam intensities of the experiment.

The final design of the extinction region and the beam dump, including any bends required for momentum selection and for critical devices, will inevitably come into play when deciding upon the final layout and location of the experimental hall.

5   Effort Summary

Tables are provided in the appendix outlining the amount of accelerator R&D and requirements development necessary to provide final details for engineering efforts. Table B outlines the necessary accelerator design efforts necessary and gives approximate efforts required to arrive at final design requirements. Table C cross-references the systems according to engineering groups. It is estimated that to arrive at physics designs and requirements necessary for cost estimating would require 6 months if performed in parallel, and a total of 3 FTE's of scientific effort.

With requirements in hand, an additional 9-12 months likely would be required to arrive at an appropriate engineering design and cost estimate for all systems, which includes a natural iterative process between the engineering and accelerator design efforts. The exact amount of effort is certainly harder to estimate today without a finalized physics design. There will undoubtedly be some amount of RF engineering R&D required and some electrical engineering R&D required, for instance for the AC dipole. However, it is clear that the accelerator systems required to address the $Mu2e$ proposal are straightforward extensions of existing and well known technologies.

6   Residual Comments

In the above an attempt was made to address the issues and associated accelerator impacts with the $Mu2e$ proposal as received. One of the major concerns brought up at the recent Director's pre-review of the experiment was the fact that the intensities expected in the Accumulator and Debuncher rings produce space charge tune shifts on the order of $\Delta\nu \sim 0.1$, which is quite high especially when trying to slowly extract particles on resonance. Since that meeting, it has been recommended to investigate other beam preparation techniques in an effort to reduce the tune spread of the extracted beam. Other approaches may be viable that would produce a different bunching scheme and beam delivery which greatly reduce the space charge effects and momentum spread of the final beam reaching the experiment. One such scenario has been suggested [9], and others will be looked at in the near future. Should one of these processes prove feasible, several of the aforementioned issues (particularly with the Accumulator/Debuncher) may be greatly alleviated making the experiment operation more robust. Such options should be examined in the very near future to optimize the overall upfront costs as well as to minimize the operational complexity and risks.

The question of ideal targeting energy has come up on occasion as well. Though the 8 GeV kinetic energy of the beam seems approximately optimal, lower energies (6 GeV or so) are often considered to be fruitful in particular with regard to antiproton backgrounds for the experiment. For production of pions it is beam power, not energy or rate individually, that counts. Unlike the Main Injector, say, with a programable ramp, the Booster has a fixed cycle time of 66.7 ms. Also, since most of the Booster losses occur at injection energy and transition, the particle output at any energy above transition would not be

significantly different. Thus lowering the energy slightly below 8 GeV would clearly lower the production rate for the experiment. Additionally, such an operation would also required the construction of a new beam line directly connecting the Booster to the Accumulator (a modified AP4 line) in order to bypass the permanent magnet Recycler ring.

Also on the subject of targeting, responsibility of the $Mu2e$ target and 8 GeV beam dump should ultimately rest with the Accelerator Division. The expertise for other recent high powered targets is in AD. The fact that multiple beam spot sizes and target materials are being discussed for the experiment implies further work to be done, and AD should play a major role in the design of the target station including plans for its future maintenance.

Finally, it should also be pointed out that if the experiment were considered on its own, without regard to NOνA, then the Proton Plan upgrades are more than enough to provide the necessary rates for $Mu2e$ from the Booster. That is, if there were no NOνA in the picture, then a Booster running at about 5 Hz would provide more than the requested rate to $Mu2e$. Of course, the injection and extraction systems, beam line connections to/from the Recycler, and the removal of Recycler beam cooling systems would still be required, part of which are anticipated to be taken care of through the NOνA project.

References

[1] Mu2e Collaboration, "Proposal to Search for $\mu^- N \to e^- N$ with a Single Event Sensitivity Below 10^{-16}," MU2E-doc-388 (`http://mu2e-docdb.fnal.gov/`) (9 Oct 2008).

[2] Mu2e Collaboration, "Expression of Interest to Fermilab," MU2E-doc-15 (1 Feb 2008).

[3] For example, see M. Syphers, $et\ al.$, "Preparation of Accelerator Complex for Muon Physics Experiments at Fermilab," Beams-doc-3220 (`http://beamdocs.fnal.gov/`) (25 Sep 2008).

[4] Proton Plan: `http://www-accel-proj.fnal.gov/Proton_Plan/index.shtml`.

[5] J. Reid, 15 Hz upgrade, internal report (draft, 21 Aug 2008).

[6] J. Reid, R. Ducar, "Booster RF Repetition Rate Limit," Beams-doc-2883 (7 May 2007); (updated 20 Aug 2008).

[7] Many suggestions and useful input come from the Antiproton Source Department, in particular S. Werkema and K. Gollwitzer.

[8] V.S. Kashikhin, D. Harding, V.V. Kashikhin, A. Makarov, D. Wolff, "Conceptual Design of AC Dipole Magnet for μ to e^- Experiment," MU2E-doc-263 (20 Aug 2008).

[9] M. Syphers, "Possible Scheme to Ameliorate Space Charge and Momentum Spread Issues," MU2E-doc-398 (21 Oct 2008).

Appendices

A   Parameter List

Table A: Parameters associated with the $Mu2e$ proposal.

p momentum on target	8.89	GeV/c
Booster Rep. Rate	15	Hz
MI cycle	20	1/(15 Hz)
Pulses per MI cycle	6	
p per Booster cycle	4	10^{12}
$\langle p/\text{sec} \rangle$ to target	18	10^{12}
$\langle p/10^7 \text{sec} \rangle$ to target	1.8	10^{20}
duty factor	90	%
Maximum stored in Recycler	—	10^{12}
Maximum stored in Accumulator	12	10^{12}
Maximum stored in Debuncher	12	10^{12}
Max. space charge $\Delta\nu$	$\sim$0.1	
Recycler RF		
53 MHz	—	kV
5.0 MHz	—	kV
2.5 MHz	—	kV
broadband	—	kV
Accumulator RF		
$h = 84$ (53 MHz)	50	kV
$h = 4$ (2.5 MHz)	—	kV
$h = 1$ (629 kHz)	4	kV
Debuncher RF		
$h = 4$ (2.35 MHz)	250	kV
$h = 1$ (590 kHz)	40	kV
Beam at Target:		
final bunch intensity	3.4×10^7	
final bunch length (rms)	30	ns
final momentum spread (rms)	8	10^{-3}
transverse emittance (95%, norm.)	< 20	π mm-mrad
length of each spill	600	ms

B Accelerator R&D List

Table B: List of accelerator R&D and requirements development necessary to provide beams to the $Mu2e$ experiment at Fermilab. Approximate efforts to arrive at final physics design requirements and lead engineering groups affected are indicated.

Accel	item	FTE	months	lead Eng.*	note
BOO	15 Hz upgrade	—	—	RF	(documented)
MI/REC	inj line/MI-8	—	—	ME, EE	(documented for NOνA)
	ext line/P1	0.1	2	ME, EE	
	stoch cool remove	0.05	0.5	ME, ...	
ACC/DEB	Rad. Safety	0.25	6	SAF	upgrade for high intensity
	ring instr.	0.25	6	INS	possible BPM, instr. upgrades
	RF req's	0.2	3	RF	new/upgraded systems
	ACC inj.	0.2	3	ME, EE	mostly kicker upgrades
	A/D transfer	0.25	6	ME, EE	relocate/new transfer line, kickers
	Slow Extr	0.25	6	ME, EE, INS	septa, correctors, feedback system
	internal abort	0.05	0.5	ME, ...	assess need for, requirements
	stoch cool remove	0.05	0.5	ME, ...	
EXT	beam line design	0.25	6	ME, EE	beam line design
	extinction insert design	0.2	3	ME, EE, INS	extinction optical insert, AC dipoles, collimators
AD/Mu2e	targeting	.25	6	ME, ...	target, dump design
	all	1.0	2		Investigate options

*nearly all will require involvement of INS, CON

C Work Breakdown List

Table C: Scope of accelerator system modifications required to provide beams to the $Mu2e$ experiment. Lead engineering groups are identified, but most systems will require combined efforts from other groups.

Eng. Sys.	Scope of estimating	note
RF	15 Hz BOO upgrade	(documented)
	ACC/DEB RF design	
ME	MI-8:REC mech. design	(part of NOνA)
	REC:P1 mech. design	
	REC stoch cooling removal	
	ACC/DEB stoch cool remove	
	ACC injection mech. design	
	A/D transfer mech. design	
	slow extract. mech. design	
	internal abort mech. design	if required
	Extraction line mech. design	
	extinction mech. design	incl. collimation
	target, dump mech. design	incl. maint. mitigation
EE	MI-8:REC elec. design	
	REC:P1 elec. design	
	ACC injection elec. design	
	A/D transfer elec. design	
	slow extract. elec. design	
	Extraction line elec. design	
	extinction elec. design	incl. AC dipole system
INS	upgrades for ACC, DEB	upgrade for bunched beam
	instr. for extraction line	incl. extinction instrumentation
	instr. for internal abort	if required
SAF	ACC, DEB tunnel	upgrade for high intensity
CON	support for all systems	general support for new elements

Note: Development of any new magnetic elements (*e.g.*, AC dipoles) are expected to be documented in Technical Division Impact Statement, though specifications will be in consultation with AD.